RANGE MEASUREMENTS OF A HIGH FREQUENCY RADIO FREQUENCY IDENTIFICATION (HF RFID) SYSTEM FOR REGISTERING FEEDING PATTERNS OF GROWING-FINISHING PIGS

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Highlights

- Range measurements were performed on a HF RFID system for registering feeding pigs.
- Factors influencing the range of the system were tested *in situ.*
- Tag, tag side, antenna and antenna quadrant were found to have little or no effect.
- Tag position and orientation did have a large influence.
- Further work is needed to cluster RFID registrations and obtain feeding patterns.

1. ABSTRACT

Monitoring the feeding pattern of a pig enables early detection of diseases and other problems. To monitor the individual feeding pattern of group-housed pigs, it has been suggested to equip the pigs with High Frequency Radio Frequency Identification (HF RFID) tags and the feeding trough with an antenna. The detection range of the HF RFID system is crucial to guarantee that all feeding pigs are detected without detecting the pigs located further from the feeder. The current study examines the factors that influence whether an antenna attached to a round feeding trough (such as those used in group housing of growing-finishing pigs) detects stationary HF RFID tags placed in various orientations and distances from the antenna.

Four experiments were performed using a custom-built test set-up that allowed determining the RFID registrations for 70 tag positions, at seven distances from the antenna and for seven orientations of the tags in relation to the antenna. In the first experiment there was determined that which tag side is closest to the antenna had very little influence on the range of registration. The results of the second experiment revealed that all eight HF RFID antennas in the pig house performed similarly, with symmetry observed in their range of registration. In the third experiment the range of the HF RFID system was measured while accounting for tag, tag position and tag orientation, whilst the last experiment was designed to test the effect of interference between tags. Reproducibility between (the order of) the tags and the average agreement between five repetitions of all tests was very high. In total, the sensitivity was 51.0 %, with a standard deviation of 43.1 percentage point (pp). The specificity was 87.1 % with a standard deviation of 19.4 pp.

It was concluded that the performance of the HF RFID system in terms of sensitivity and specificity of the range depends greatly on the height and orientation of the tags. This causes irregular gaps to appear between subsequent RFID registrations of a feeding pig. To improve the performance of the system in practice, it is suggested to adjust the height of the antenna to better match the size of the pigs and to develop algorithms and criteria to merge raw RFID registrations into relevant feeding variables for individual pigs.

Keywords: growing-finishing pigs, radio frequency identification, feeding pattern, range measurement

2. INTRODUCTION

With increasing herd sizes in livestock farming and a decreasing labour time available per animal, adequate individual monitoring of animals becomes difficult. Therefore, automated monitoring of farm animals can be helpful and, in addition, might avoid economic losses (Frost et al., 1997; Pluym et al., 2013). Automatic control of the pigs' environment is already common practice, but behavioural measurements with the potential to improve production efficiency are still lacking (Wathes et al., 2008; Maertens et al., 2011). Problems with health, welfare and productivity in growing-finishing pigs are thought to be associated with alterations in feeding behaviour, possibly in an early stage of problem-development. Automatic registration of pigs' feeding patterns may therefore provide added value for farmers as well as researchers (Hart, 1988; Weary et al., 2009).

To measure the feeding pattern of an individual pig, the feeding pig must be both detected and identified while feeding. Video tracking or automated image analysis makes it possible to detect feeding pigs, but identification is very difficult (Lind et al., 2005; Ahrendt et al., 2011). Radio Frequency Identification (RFID), which includes a number of different techniques for wireless transfer of data between a data-carrying device (transponder or tag) and a reader by means of (electro)magnetic fields (Finkenzeller, 2010), can detect and identify an individual animal using one sensor (Artmann, 1999; Eradus and Jansen, 1999; Ruiz-Garcia and Lunadei, 2011). The use of RFID for animals is widespread and is typically limited to passive Low Frequency (LF) systems with an operating frequency of 134.2 kHz (ISO 11784 & 11785) (Artmann, 1999; Finkenzeller, 2010).

Computerised feeding stations using LF RFID have been used to measure pigs' feeding patterns in research since the early 1990s. For growing-finishing pigs electronic feed stations have been developed and used to log time and duration per feeding visit as well as the feed intake of the individual pig (Hyun et al., 1997; Bruininx et al., 2001a; Bruininx et al., 2001b; Hyun and Ellis, 2002). Electronic sow feeders have been used in research (Cornou et al., 2008) as well as in practice (pig farmers with group housing of gestating sows) (Tuyttens et al., 2011). However, these feeders only allow access to one pig at a time and mostly only one feeder is available per group. In most commercial growing-finishing pig houses multiple feeders with multiple feeding places are used.

Efforts have been made to integrate RFID systems into the commonly-used, commercially available feeders for group-housed pigs. Brown-Brandl and Eigenberg (2011) and Brown-Brandl et al. (2013) have achieved good results with LF RFID antennas in rectangular-shaped feeders. LF RFID currently does not provide the possibility to read multiple tags at the same time. For this reason, one LF antenna had to be installed per feeding place. RFID systems operating at higher frequencies exist. These systems allow multiple tags in the range to be read simultaneously, by integrating anti-collision algorithms. This makes it possible to use only one antenna per feeder with multiple feeding places, leading to a system which is more cost-effective and practical. Reiners et al. (2009) and Hessel and Van den Weghe (2011) have demonstrated the potential of a High Frequency (HF) RFID system with an operating frequency of 13.56 MHz for identifying piglets feeding at a round trough.

When designing a HF RFID system to detect feeding pigs in a commercial pig house, the range of registration is crucial. The pigs grow quickly (which changes the height of the tag), the pens are crowded, and the pigs jostle each other around the feeder as they compete for food. To detect only the feeding pigs, the HF RFID system's range should provide good coverage of the area above the feeding trough but should not detect tags outside of that area. The range of a HF RFID system depends on numerous factors: the operating frequency, the type of tags used, the type of reader used, the size of tags and antenna, environmental influences, etc. (Finkenzeller, 2010; D'hoe et al., 2011). The theoretical range of an RFID system as measured by the manufacturer (often in optimal circumstances) can differ substantially from the achieved range in a real-life situation (Ciudad et al., 2010). Extensive range measurements *in situ* could provide valuable information on where and when feeding pigs will be registered by the HF RFID system, and whether this range is sufficiently accurate to discriminate feeding pigs from pigs moving close to the trough but who are not feeding. Well-designed experiments can also provide insight into which factors influence the range of the HF RFID antenna. Although the presented HF RFID system and other RFID systems used to measure animal feeding behaviour were validated online (using feeding animals) (DeVries et al., 2003; Brown-Brandl and Eigenberg, 2011; Maselyne et al., 2014), we could not find any well-designed experiments to measure the range of an RFID system in practice and to determine the factors that influence that range. These measurements could provide more insight into the functioning and limitations of RFID systems however.

To investigate the factors influencing the detection range of a HF RFID system for the monitoring of pig feeding patterns, we have performed various range tests. The objectives of the study were (1) to determine the effect of antenna, antenna quadrant, tag side (up or down), tag, tag position and tag orientation on the RFID registrations, and (2) to calculate sensitivity, specificity, reproducibility and repeatability for the range of the HF RFID system in this application.

3. MATERIALS AND METHODS

3.1. MATERIALS

3.1.1. PIG HOUSE AND HF RFID SYSTEM

The tests were performed in a pig house at the experimental farm of the Institute for Agricultural and Fisheries Research (ILVO, Melle, Belgium). The pig house was divided in four pens with eight feeders in total (Swing MIDI, Big Dutchman Pig Equipment GmbH, Vechta, Germany) (feeder positioning illustrated in Figure 1). The feeders had a round metal trough with a diameter of 450 mm and an edge with height of 110 mm from the ground. To register transponders near the feeder, a round High Frequency (HF) RFID antenna (custom-made by DTE Automation GmbH, Enger, Germany) was attached to the feeders above the trough (Figure 2a). The diameter of the antenna was 390 mm, the internal diameter of the plastic housing was 350 mm, and the external diameter was 430 mm. The underside of each antenna was 50 cm from the ground. The antennas were tuned on-site to achieve the correct resonance frequency of 13.56 MHz. This is necessary to adjust the system to any fixed environmental influences on the resonance frequency (for example metal or electromagnetic fields in the environment). A tuning board (i.e. a connector between antenna loop and data cable used to tune the antenna to the correct resonance frequency before installation) can be seen on one side of the antennas (Figure 2a). This was named the 'tuning side' of the antenna, in contrast to the here-after called 'other side' of the antenna. Also, a 'left side' and a 'right side' were assigned. Conventions for these names can be seen in Figure 2a. Each antenna was assigned a letter from 'A' to 'H'.

Each antenna was connected to one of two HF long range readers (ID ISC.LR2500-A, FEIG ELECTRONIC GmbH, Weilburg, Germany) through two multiplexers (ID ISC.ANT.MUX-A, FEIG ELECTRONIC GmbH, Weilburg, Germany), following the scheme in Figure 1. Antennas A, B, G and H were connected to reader 2, while antennas C, D, E and F were connected to reader 1. Data communication between the readers and a desktop PC was performed through the RS232 standard with the use of an USB-RS232 adapter for interfacing with the PC where all the RFID registrations were logged. The log file contained 1) the time stamp of the RFID registration (to the second), 2) the unique code of the RFID tag and 3) the antenna or feeder where it was registered.

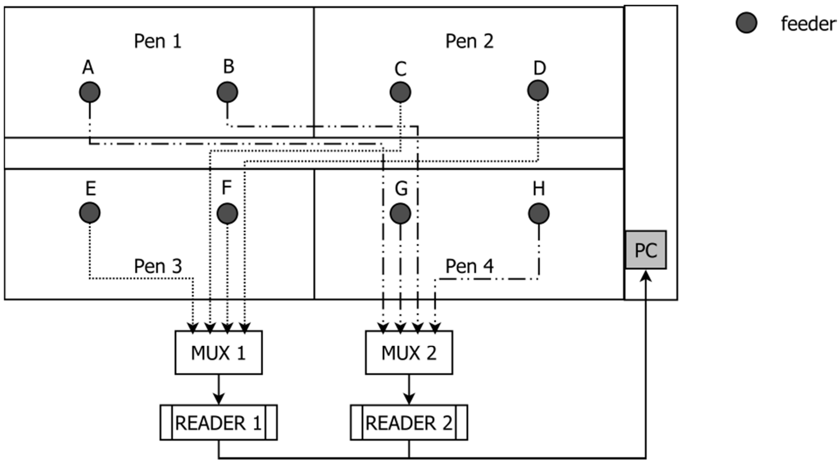

Figure 1: **Floor plan of the pig house indicating the position of the feeders in the pens and the connections of the RFID antennas to the two multiplexers (MUX 1 and MUX 2) and the readers (READER 1 and READER 2). Both readers are connected to a PC in the control room next to the pig house.**

The tags used were IN Tag 300 I-Code SLI tags (ISO 15693, HID Global Corporation, California, USA) with a diameter of 30.0 mm, a thickness of 2.5 mm and an enlarged hole of 7.8 mm. These HF RFID tags fit onto the pin of standard pig ear tags and had approximately the same diameter as the standard ear tags. For the RFID tags, a 'tag side 1' (the side where the HID brand name is visible) and 'tag side 2' (the other side) were assigned (Figure 2b). When a tag comes in 'range' of the antenna, this means that the inductive coupling between tag and antenna is strong enough to power up the tag sufficiently so it can 'send' its ID code back to the antenna. When this tag code is picked up by the antenna and decoded properly, we say that the tag is in range of the antenna.

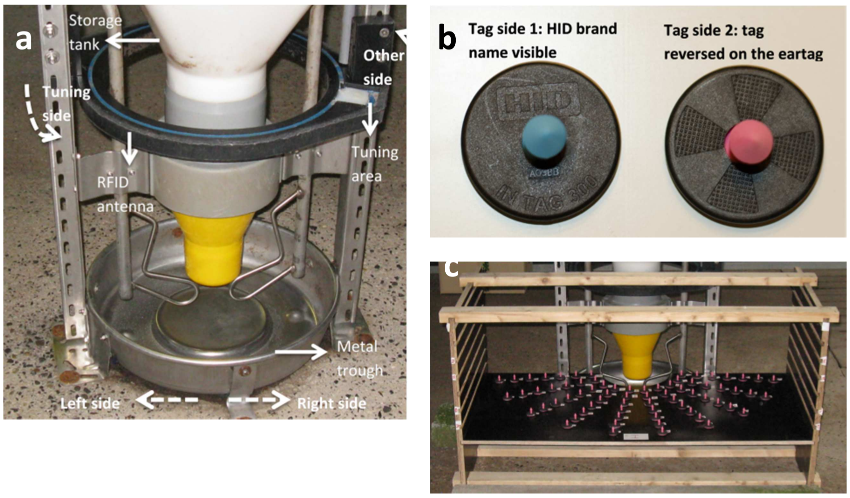

Figure 2: (a) Pig feeder with an RFID antenna attached around the storage tank above the metal trough, the conventions used are: the 'tuning side' is the front half of the antenna (containing the tuning board); the 'other side' is the back half of the antenna; the 'left side' is the left half and the 'right side' is the right half of the antenna, seen from the perspective of the figure; (b) HF RFID tag, the conventions used are: 'tag side 1' is the side where the HID brand name is visible; 'tag side 2' is the side without imprinted letters visible; (c) Portable wooden frame placed underneath one half of the RFID antenna with a testing board placed at height 15 cm.

3.1.2. TEST EQUIPMENT

To measure the range of the HF RFID system a portable wooden frame (height 50 cm, width 100 cm, depth 50 cm) that could accommodate a wooden board with tags glued to it was placed around one half of the feeder (Figure 2c). Four wooden boards (100 cm x 50 cm), each with a semicircle (radius 11 cm) cut out to accommodate the storage tank of the feeder, were used. On each of the four boards, the tags were placed at different orientations relative to the antenna. The frame was made to hold the boards horizontally at seven heights: 15, 20, 25, 30, 35, 40 and 45 cm. Because the presence of metal and water in the close neighbourhood of an RFID antenna or tag has negative effects on the performance and range, the frame was made entirely out of dry wood and glue (Ciudad et al., 2010; D'hoe et al., 2011).

On each board, concentric semi-circles of diameters 30, 40, 50, 60, 70, 80 and 90 cm were drawn (Figure 3). The centre of the removed semi-circle was used as the centre of the concentric semi-circles. Lines were drawn outwards from the mutual centre of the circles starting at 9° from the edge of the board and subsequently at 18° from each other. Seventy standard ear tags were then placed at the intersections of the semi-circles and the lines. These ear tags could hold 70 HF RFID tags in a chosen order on the board. In Table 1 the horizontal distances of the tags on each semi-circle versus the antenna and the feeder edge are summarized.

The four boards had different layouts as shown in Figure 3: (a) On board I the ear tags were glued flat onto the board's surface, placing the tags horizontally. (b) On board II the ear tags were glued to one side of cuboid wooden blocks that were attached to the board, placing the tags vertically. On the left side of the board, the ear tags were placed with their pin pointing towards the centre of the feeder; on the right side of the board, the pins pointed towards the left side of the feeder (or in clockwise direction seen from above). (c) Boards III and IV were fitted with half-cubical, diagonally-cut wooden blocks (blocks were cut in half along the face diagonals of the two opposite faces). The ear tags were glued onto the side of the blocks. The tags were placed under 45° relative to the horizontal plane. The pins of the ear tags were oriented as follows: on the left side of board III, they were oriented towards the feeder; on the right side of board III, away from the feeder; and on board IV, to the right side of the feeder (or in counterclockwise direction seen from above). In Table 1 the vertical distances of the tags on each board versus the antenna and the feeder edge are summarized.

We assumed that the range of the RFID antennas was symmetrical along the line drawn between the left and right side of the board. Assuming this symmetrical range, the four configurations of the tags allowed the range of the RFID antenna to be measured for seven orientations of the tags as follows: one orientation under 0° respective to the antenna (board I), two possible orientations under 90° (left and right side of board II), and four possible orientations under 45° (left and right sides of board III and IV). When positioning the portable wooden frame underneath one half of the RFID antenna and placing one of the tag-covered boards at a certain height in the frame, the range of the RFID antenna could be measured by logging which tags were registered and noting their position (Figure 2c).

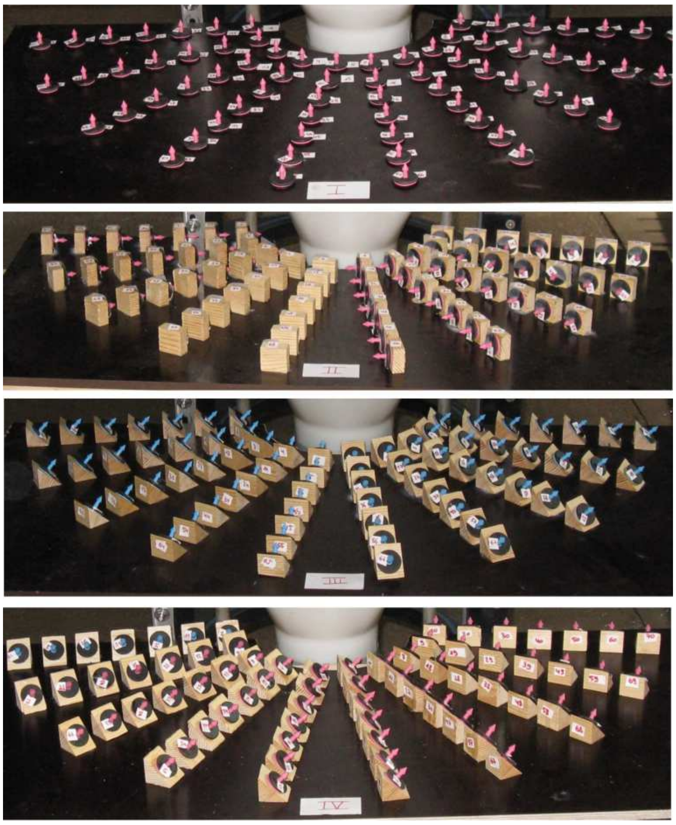

Figure 3: Layout of the four wooden boards used; top: board I with the ear tags placed horizontally; second: board II with the ear tags placed vertically with the pins on the left side of the board pointing towards the feeder and the pins on the right side of the board pointing to the left side of the feeder (clockwise direction); third: board III with the ear tags placed under 45° with the horizontal plane with their pin pointing towards the feeder on the left side of the board and away from the feeder on the right side of the board; bottom: board IV with the ear tags placed under 45° with the horizontal plane with their pin pointing to the right of the feeder (counterclockwise direction).

Diameter semi-circle [cm]	Horizontal distance from the antenna [cm]		Horizontal distance from the feeder edge [cm]	
30	-4.5*		-7.5*	
40	0.5		-2.5*	
50	5.5		2.5	
60	10.5		7.5	
70	15.5		12.5	
80	20.5		17.5	
90	25.5		22.5	
Height of board [cm]	**Vertical distance from the antenna [cm]**		**Vertical distance from the feeder edge [cm]**	
	Board I	**Board II, III and IV**	**Board I**	**Board II, III and IV**
45	3.5	2	35.5	37
40	8.5	7	30.5	32
35	13.5	12	25.5	27
30	18.5	17	20.5	22
25	23.5	22	15.5	17
20	28.5	27	10.5	12
15	33.5	32	5.5	7
*Negative numbers are inside the antenna or feeder circle				

Table 1: Overview of distances from the tag centres to the antenna and feeder edge, in the horizontal direction for the different semi-circles and in the vertical direction for the different heights of the boards.

3.2. EXPERIMENTS

The experiments were performed with the antennas and readers described in section 3.1, whilst keeping the influence of the environment in the pig house constant. Seventy HF RFID tags were randomly chosen from a batch of 500; these were labelled 1 through 70. By using a multiplexer, each antenna was addressed separately and turn-by-turn with the cycle time depending on the number of antennas (four) connected to the multiplexer and the number of tags in the identification area. All tests (for either tuning side or other side, for each height and each repetition) consisted of placing the board on the correct height and leaving it at this position during at least 10 s. This allowed sufficient time to have at least one read-cycle of the antenna per test (in other words, the multiplexer addressed the antenna at least once during that 10-second interval). We also know from previous experiments that very short feeding visits were no exception for pigs housed in large groups with the same feeders and HF RFID system as presented here (Maselyne et al., 2014), hence the choice of 10 s tests and not longer. Start and stop times were recorded for each test and logs were made of which RFID tags were registered during the tests.

In the **first experiment** (E1) it was investigated whether the side of the RFID tag being closest to the antenna (the side imprinted with the HID brand name vs. the other side, Figure 2b) could influence the registrations. Using board I, the tuning side of antenna H was tested at all heights (15 cm till 45 cm at 5 cm-intervals). First the RFID tags were placed with the side imprinted with the HID brand name visible (‘tag side 1’). Subsequently all the RFID tags were placed in the same location on the board, but were turned over so the HID brand name was facing toward the ear tag and the board ('tag side 2'). All heights were tested five times in random order.

The **second experiment** (E2) was designed to determine the influence of antenna and antenna quadrant on the RFID registrations. Each antenna (labelled 'A' to 'H') in the pig house was tested on both sides (the side containing the tuning board and the other side, Figure 2a) using board I at three heights: 20, 30 and 40 cm. All heights were tested five times in random order. The tags were placed with the HID brand name visible ('tag side 1').

The range of the tuning side of antenna H was measured in the **third experiment** (E3), taking the effect of tag, tag position and tag orientation on the registrations into account. All heights were tested five times in random order with all four boards, except for height 45 cm which was not possible with boards II, III and IV due to the height of the wooden blocks. This test was performed with the tags placed with the HID brand name visible ('tag side 1') using two random orders of the tags on the board. This was done both to determine and eliminate the effect of the tag on the range.

A short **fourth experiment** (E4) was performed to test if interference between the tags would influence the results. Board I was used for all heights at the tuning side of antenna H. The board was filled with only 35 tags instead of 70, with each time one ear tag left empty in between (like a checker board pattern). Each height was tested once. Then, the board was filled again with 35 tags but now placed on the positions that were left empty in the previous tests, again each height was tested once. Taking the results of both tests together (so that every position was measured once) and comparing them to the results of E1 (tag side 1) or E3 (board I) allows checking if the tags being close to each other or the amount of tags on the board would influence the results.

Table 2 gives an overview of the experiments.

Experiment	Antenna	Antenna side	Board	Height of board [cm]	Tag order	Tag side	Repetitions
1	H	Tuning	I (0°)	15, 20, 25, 30, 35, 40, 45	1	1 (HID brand name visible), 2 (no imprinted letters visible)	5 (random)
2	A, B, C, D, E, F, G, H	Tuning, Other	I (0°)	20, 30, 40	1	1	5 (random)
3	H	Tuning	I (0°), II (90°), III (45°), IV (45°)	15, 20, 25, 30, 35, 40, 45*	1, 2	1	5 (random)
4	H	Tuning	I (0°)	15, 20, 25, 30, 35, 40, 45	1	1	1 (once with 35 tags on the board, then once with the other 35 tags on the board)
* Height 45 cm was only tested for board I							

Table 2: Overview of the performed experiments. Cfr. Figure 3 for the layout of the four boards used.

3.3. STATISTICAL ANALYSIS

3.3.1. REPRODUCIBILITY AND REPEATABILITY

Reproducibility was calculated here as the percentage agreement between reproductions of a test. Reproductions are tests where all but one factor was kept constant. The factors that were changed were: the tag side that was facing upwards, another antenna that was used, another side of the antenna that was tested or the tag order that was changed. Repeatability was calculated as the percentage agreement between repetitions of a test, where all factors were kept constant. The time intervals between reproductions or repetitions of the same test were kept as short as possible.

Effect of the side of the tag (i.e. which tag side is closest to the antenna) on the range of the HF RFID system (depicted here by all the measurement points of the experiment) can be determined from E1 by calculating the percentage agreement between the tests with the same height but with different tag sides presented. The percentage agreement for every height, as a measure for the reproducibility between tag sides, was calculated as:

$$Perc.agreement\ [\%] = 100 - \frac{100}{70}\sum_{t=1}^{70}\left|R_{t,tag\ side\ 1} - R_{t,tag\ side\ 2}\right|; \qquad (1)$$

With t the tag position (1 to 70) and $R_{t,tag\ side}$ the number of repetitions during which the tag at position t was registered (minimum one registration during the 10-second test) divided by the total number of repetitions performed.

The reproducibility among the different HF RFID antennas can be determined from E2 by comparing the agreement between all eight antennas. In the same manner as in equation (1), the symmetry of the antennas can be determined through the percentage agreement of the tuning side and other side and of the left and right side of each antenna.

The reproducibility of tags can be calculated by looking at both orders of the tags on the boards in E3 and calculating their percentage agreement.

In E3 each height (except for 45 cm for boards II, III and IV as mentioned above) was tested five times for each board, under the same circumstances (factors such as side of the tag, tag and antenna were constant) and in random order. In this way, the repeatability of the HF RFID system can be calculated by means of calculating the percentage agreement between all five repetitions.

3.3.2. RANGE, SENSITIVITY AND SPECIFICITY

In the experiments we measured the range of the HF RFID system for different orientations of the tags relative to the antenna. To determine the sensitivity and specificity of the RFID antenna the desirable range of the system had to be defined. The cylindrical area above the trough and below the antenna was defined as the target area for tag registration; this is where the RFID tags in the feeding pigs' ears would be located in practice. The RFID tags outside of this cylindrical area should therefore not be registered. Twenty positions inside the target area (positions 1 – 20, on the two inner semi-circles) were identified. These positions lay within a radius of 20 cm from the centre of the antenna, see also Table 1 (the radius of the trough is 22.5 cm). The remaining 50 positions were outside the desired target area. The sensitivity and specificity for every height were calculated as:

$$Sens.[\%] = \frac{TP}{P} = \frac{100}{20}\sum_{t=1}^{20} R_t\,; \qquad (2)$$

$$Spec.[\%] = \frac{N - FP}{N} = 100 - \frac{100}{50}\sum_{t=21}^{70} R_t\,; \qquad (3)$$

t = the tag position;

TP = the number of true positives = the number of registrations inside the target area;

P = the number of positives = the number of positions in the target area (so positions 1 – 20, on the two inner semi-circles) multiplied by the number of repetitions;

R_t = the number of repetitions during which the tag at position t (one of the 70 positions that the tags can take on the board) was registered (minimum one registration during the 10-second test) divided by the total number of repetitions performed;

FP = the number of false positives = the number of registrations outside the target area;

N = the number of negatives = the number of positions outside the target area (so positions 21 - 70, on the five outer semi-circles) multiplied by the number of repetitions.

By comparing the achieved sensitivity and specificity in E1 or E3 (board I) with E4, changes in the results if less tags are on the board or in range of the antenna or if the tags are less close to each other can be determined. The sensitivity and specificity calculated for E3 give the best idea on how good the system is for measuring feeding pigs, since this was the most extensive experiment.

4. RESULTS

In total 70, 240, 250 and 14 tests were performed in experiments 1, 2, 3 and 4, respectively. For one stationary tag in range of the antenna, the cycle time was determined to be 2 ± 1 s (mean ± SD). By leaving the tags in position for minimal 10 s, at least one (average five) complete read-cycle occurred during the test. When a tag at a certain position was registered at least once during a test, the position was marked as registered during that test.

The test duration of 10 s was chosen arbitrarily as five times the cycle time, without making the tests too long (as pigs can have very short feeding visits (Maselyne et al., 2014)), but this could have influenced the results. For E1, when a tag was registered during a test, only in 50 % of the cases the tag was registered five times or more during that test. So, half of the registered tags were registered less often than we would have expected. If the tests would last longer, it is thus possible that even more tags would be registered.

During some tests no registrations occurred, despite having several tags in range of the antenna (confirmed during other tests in the same circumstances). In the error files of the logging software of the HF RFID system, consecutive ‘RF communication errors’ (indicating tag collisions) were observed during those failed tests. Sometimes only one or a few errors occurred during a test without having a profound effect on the outcome of the test but sometimes the entire test was disturbed.

Tests with ‘RF communication errors’ that hindered all registrations during a test were removed from the analysis because these errors would have a dramatic impact on the analysis. Furthermore, they rarely happen when the tags are attached to pigs, as confirmed by the frequency of occurrence of these errors under practical conditions when pigs were in the pen and registered at the feeder. The number of ‘RF communication errors’ in real-life circumstances corresponded to only 0.14 % of data lost in the entire pig house (eight feeders, 295 pigs wearing tags during five days of registrations) (unpublished data).

4.1. EXPERIMENT 1

The plots in Figure 4 illustrate the results of E1, which included the number of tests in which the tag was registered at least once for each height and each position. At a testing height of 15 cm no tags were registered, so these empty plots are not shown. On the left side of Figure 4, the measurements are shown for all tags with the HID brand name visible (‘tag side 1’); on the right side, the results are shown for all the tags on tag side 2. For tag side 2, the data of one repetition at a height of 25 cm and one repetition at a height of 45 cm were lost due to the abovementioned ‘RF communication errors’.

As the height increases (which decreases the distance between the tag and the antenna), the registration area becomes larger. Between heights of 25 cm and 40 cm the range provides good coverage of the feeding trough area (the two inner circles in Figure 4). At a height of 45 cm (within a vertical distance of 5 cm from the antenna), the range is larger, but it does not exceed a horizontal distance of 15 cm from the antenna and feeder edge (Figure 4). The registered area is very similar between both tag sides (Figure 4). The percentage agreement between both tag sides for the different heights was 98.8 % on average with a standard deviation (SD) of 1.0 percentage point (pp). Averaged across heights and tag sides, the sensitivity of the system during E1 was 59.9 % ± 39.5 pp (mean ± SD) and the specificity was 92.3 % ± 19.5 pp (mean ± SD).

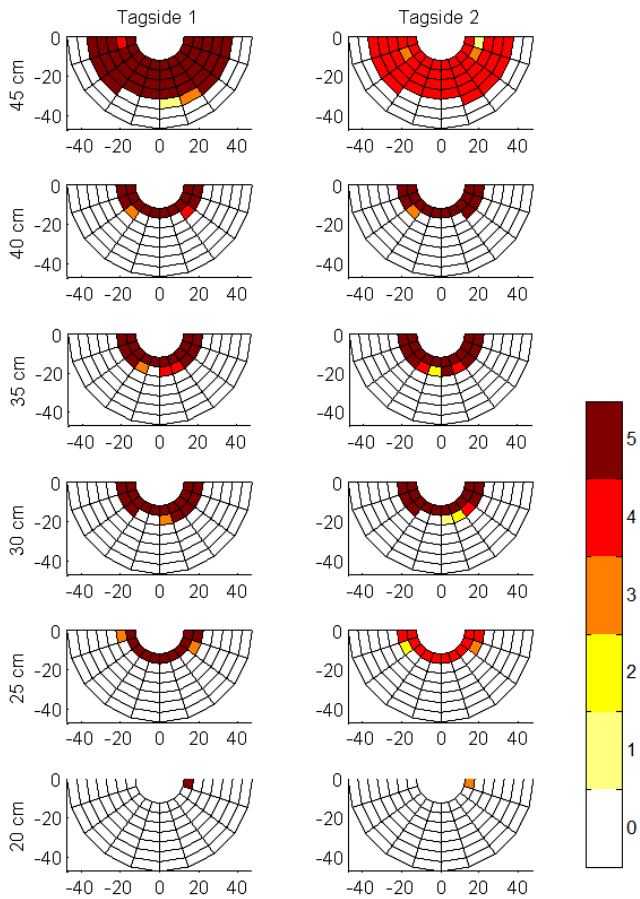

Figure 4: Results of experiment 1 at antenna H, tuning side, 6 heights (15 cm is not shown) with: left: tags with brand name visible (tag side 1); right: tags with brand name facing towards the ear tag and board (tag side 2) (Cfr. Figure 2b). The color map represents the number of repetitions during which the RFID tag at that position was registered at least once. Top side of each plot is in the direction of the feeder.

4.2. EXPERIMENT 2

Figure 5 depicts the results of testing three heights at all eight antennas (tuning side and other side). A separate plot is shown for each antenna and each height, with the tests for the tuning side of the antenna on the bottom half of the plot and the tests of the other side of the antenna on the top half. On the tuning side of antenna D, data of one repetition at a height of 20 cm was lost due to recurring 'RF communication errors' during the entire test. The same problem occurred during two repetitions at height 40 cm on the other side of antenna G.

The range of detection increases as the distance from the antenna decreases. This is very similar for the height of 30 cm and 40 cm. Apart from some small exceptions (possibly due to the antennas not having exactly the same height and not being perfectly horizontal), the antenna ranges are very similar between antennas. The agreements between the eight antennas for each testing height are summarised in Table 3. On average, the percentage agreement between the antennas was 97.2 % with a SD of 1.9 pp.

Figure 5 shows that the range of the antenna is spherical and symmetrical on all sides. The percentage agreement between the tuning side and the other side of the antennas at the different heights was 96.8 % on average with a SD of 3.4 pp, while the percentage agreement between the left and the right side of the antennas was 97.8 % with a SD of 1.7 pp. Sensitivity of the system during E2 was 54.8 % ± 36.4 pp (mean ± SD) and the specificity was 99.4 % ± 1.7 pp (mean ± SD).

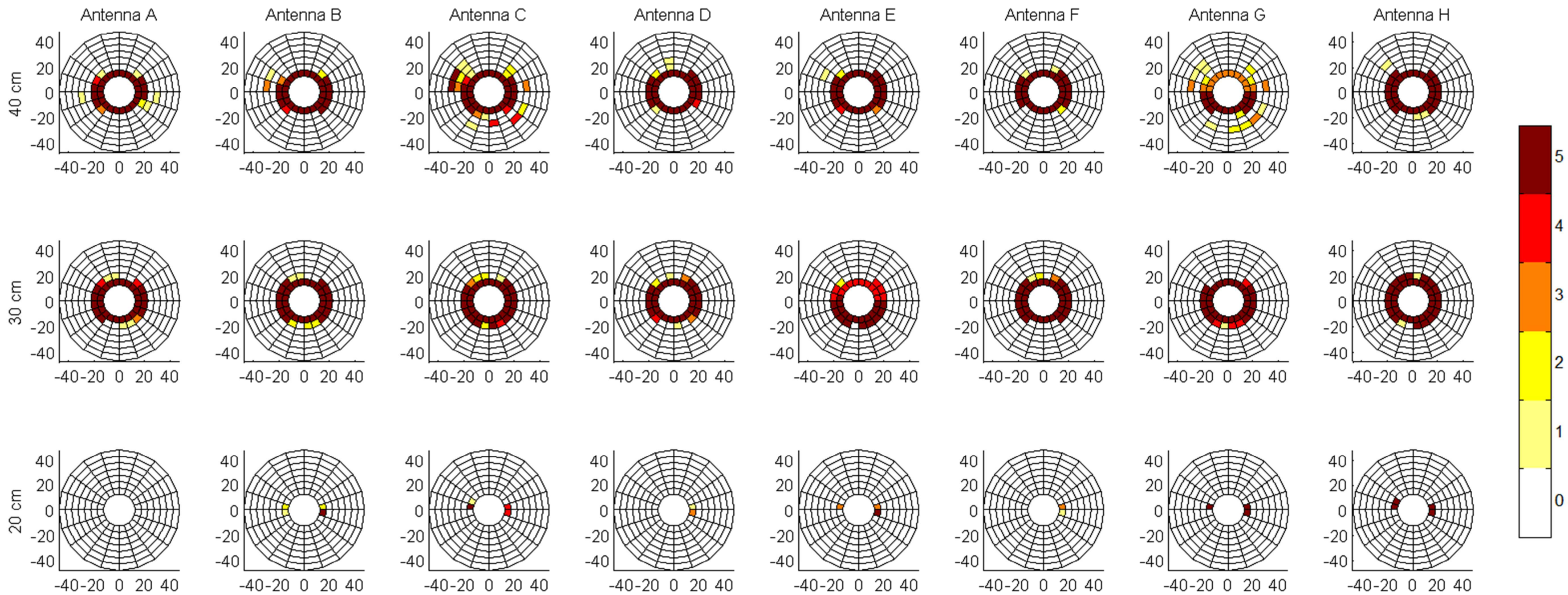

Figure 5: Results of experiment 2 at antenna A to H, tuning and other side, 3 heights (20, 30, 40 cm). The color map represents the number of repetitions during which the RFID tag at that position was registered at least once. Bottom half of each plot is the tuning side of the antenna, top half is the other side.

Percentage agreement [%]							
Antenna	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Height 40 cm							
A	97.3	92.9	97.9	97.6	97.6	93.3	96.4
B		94.7	96.9	98.3	97.4	95.7	97.4
C			92.4	93.9	93.0	95.0	93.3
D				98.6	98.9	92.6	97.4
E					98.9	94.0	98.6
F						93.2	97.7
G							94.0
Height 30 cm							
A	98.9	97.0	98.7	95.4	98.6	97.3	96.1
B		97.9	97.9	96.0	98.6	97.9	97.0
C			96.6	96.7	97.0	98.3	97.1
D				95.0	98.7	96.9	96.0
E					94.6	97.3	94.7
F						96.4	97.0
G							96.0
Height 20 cm							
A	98.6	98.0	99.3	98.4	99.4	97.9	97.1
B		98.9	99.3	99.6	98.9	99.0	98.3
C			98.7	99.3	98.6	99.6	99.1
D				99.1	99.3	98.5	97.8
E					99.0	99.4	98.7
F						98.4	97.7
G							99.3

Table 3: Percentage agreement (%) between the eight antennas in the pig house tested in experiment 2 at heights 40, 30 and 20 cm.

4.3. EXPERIMENT 3

Figure 6 illustrates the results of the range measurements of E3. This experiment was performed at the tuning side of antenna H, with the four boards at all possible heights. Five repetitions were performed, with two orders of the tags on the boards, so in total every height was tested 10 times for each board. The 'RF communication errors' hindered entire tests at several instances: three at board I (2nd order of tags: three at 45 cm), 10 at board II (1st order of tags: three at 25 cm, five at 30 cm; 2nd order of tag: two at 35 cm), 16 at board III (1st order of tags: five at 15 cm, four at 30 cm, two at 35 cm; 2nd order of tags: five at 20 cm) and one at board IV (1st order of tags: one at 25 cm).

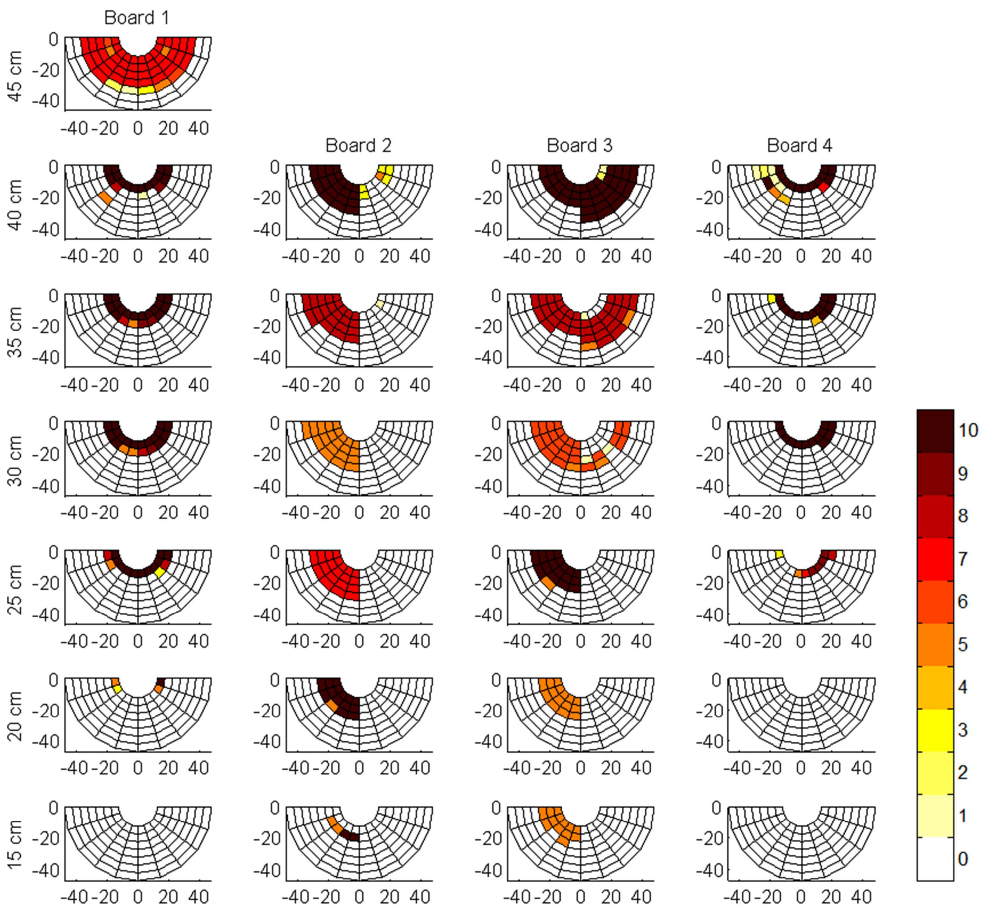

Figure 6: Registered positions during experiment 3 at all heights at the tuning side of antenna H. The color map represents the number of repetitions during which the RFID tag at that position was registered at least once (two tag orders were tested five times each). Top side of each plot is in the direction of the feeder. Cfr. Figure 3 for the layout of the four boards used.

For all orientations, the range increases as the distance from the antenna decreases. However, the specific size and shape of the range depends highly on the orientation of the tags in relation to the antenna (Figure 6). The range never exceeds more than 15 cm outside the feeding trough and in general provides good coverage of the feeding trough (see Table 1 for the horizontal distances of the tags versus the feeder edge). In Table 4 the number of registrations is expressed as a percentage of the maximum possible number of registrations, (corrected for the missed tests due to 'RF communication errors') for every height and every semi-circle the tags are placed on. No distinction between orientations of the tags was made in this table. In Table 1 the corresponding vertical or horizontal distance from the tag centre to the antenna or feeder edge can be found, for every height and semi-circle used. Table 4 thus summarises the reading range of the HF RFID system expressed in horizontal and vertical distances from the antenna or feeder edge, for the total of all orientations tested.

[%]	Diameter semi-circle [cm]						
Height of board [cm]	**30**	**40**	**50**	**60**	**70**	**80**	**90**
45	100	92.9	100	100	74.3	0	0
40	86.0	61.8	42.8	26.5	12.5	0	0
35	78.3	68.9	33.3	28.9	13.9	0	0
30	82.3	55.5	24.2	24.8	1.6	0	0
25	65.6	35.3	23.6	16.7	0	0	0
20	28.0	21.4	20.0	0	0	0	0
15	7.1	15.7	4.3	0	0	0	0

Table 4: Number of registrations as a percentage of the maximum possible number of registrations (corrected for the tests missed due to errors) in experiment 3 for every height and every semi-circle, with all boards taken together.

The reproducibility between (orders of) tags on the board was 97.6 % with a SD of 2.1 pp. In Table 5 the percentage agreement between the two tag orders is shown for all heights and all boards. Tag orders could not be compared at height 30 cm on board I and at height 15 and 20 cm on board III as all repetitions of one of the tag orders were lost at those heights due to 'RF communication errors'.

Percentage agreement [%] between tag orders				
Height [cm]	**Board I**	**Board II**	**Board III**	**Board IV**
45	92.3			
40	97.4	94.9	99.7	96.0
35	97.4	99.7	96.7	98.0
30	96.3		95.4	100
25	96.6	100	98.6	96.7
20	96.3	98.6		100
15	100	97.1		100

Table 5: Percentage agreements (%) between the two tag orders tested in experiment 3, at all heights, with all boards.

The average agreement between the five repetitions of all tests with the first order of tags on the board was 99.1 % with a SD of 1.5 pp. Table 6 summarises the sensitivity and specificity of the HF RFID system for the different tag orientations and tested heights. On average, the sensitivity was 51.0 % with a SD of 43.1 pp and the specificity was 87.1 % with a SD of 19.4 pp. The performance of the RFID system in terms of sensitivity and specificity of the range appears to be highly dependent on the height and orientation of the tags.

Sensitivity [%]								
Height [cm]	**Board I**	**Board II**		**Board III**		**Board IV**		**Average**
		Left	**right**	**left**	**right**	**left**	**right**	
45	96.4							96.4
40	79.0	100	20.0	100	83.0	53.0	77.0	73.1
35	95.5	100	1.3	100	51.3	53.0	84.0	69.3
30	93.5	100	0	100	0	50.0	80.0	60.5
25	67.0	100	0	100	0	8.9	56.7	47.5
20	11.5	100	0	100	0	0	0	30.2
15	0	30.0	0	100	0	0	0	18.6
Specificity [%]								
45	45.1							45.1
40	99.0	60.0	100	80.0	40.0	91.2	100	81.5
35	100	52.0	100	68.0	43.0	100	100	80.4
30	100	56.0	100	60.7	71.3	100	100	84.0
25	100	60.0	100	70.0	100	100	100	90.0
20	100	82.0	100	80.0	100	100	100	94.6
15	100	100	100	88.0	100	100	100	98.3

Table 6: Sensitivity and specificity of the RFID system for the different tested heights and orientations of the tags. Cfr. Figure 3 for the layout of the four boards used.

4.4. EXPERIMENT 4

The sensitivity of the joint tests of E4 (so the 2 tests with 35 tags taken together so that each of the 70 positions was measured) was 0 % at 15 cm, 20 % at 20 cm, 75 % at 25 cm, 95 % at 30 and 35 cm, 80 % at 40 cm and 100 % at a height of 45 cm. Specificity was 100 % for all heights, expect 45 cm, where the specificity was only 42 %. On average, the sensitivity was 66.4 % ± 40.0 pp (mean ± SD) and the specificity was 91.7 % ± 21.9 pp (mean ± SD) in E4.

Compared to E1 (tag side 1), with a sensitivity of 60.1 % ± 41.2 pp (mean ± SD) and E3 (board I, both tag orders), with a sensitivity of 59.1 % ± 38.3 pp (mean ± SD), the sensitivity was a bit higher in E4. The specificity in E4 was slightly lower than in E1 (tag side 1: 92.3 % ± 20.3 pp (mean ± SD)) and E3 (board I: 94.4 % ± 14.5 pp (mean ± SD)). With only half the tags simultaneously on the board and more distance between the tags, the range was thus a bit larger for horizontally placed tags. Interference did play a role in the tests, but only for tags that were on the border of the range of the RFID antenna. No changes in the shape of the range were seen between E4 and the other experiments.

5. DISCUSSION

This paper provides (1) a methodology for measuring the range of an RFID system in practical situations and (2) insights into the functioning and limitations of a HF RFID system designed to monitor feeding pigs in group-housing. The experiments performed show that only position and orientation of the tags influence registrations. Repeatability and reproducibility were high. On average, specificity was 87.1 % and sensitivity 51.0 %. The required sensitivity and specificity of the range depend on the application and on what happens with the performance when tags are attached to pigs. The less stress on the feeder, the better the performance of the HF RFID system will likely be (no pigs waiting for access, longer visits). Even with a highly stressed feeder (feeding ratio of between 7:1 and 15:1), Maselyne et al. (2014) showed that a sensitivity of 88.6 % and a specificity of 98.3% is achievable for the HF RFID system in registering feeding pigs.

The results obtained in this paper depend on several choices made for the experiments. First, the duration of the tests (10 s) could have played a role, since not all tags were registered continuously during these 10 s. Maselyne et al (2014) found that pigs housed in large groups with the same feeders and HF RFID system presented here, had feeding visits that were on average 42 s long. Some pigs had an average duration of a feeding bout of only 20 s however with a standard deviation of the same order of magnitude. We know from those experiments that very short feeding visits were no exception, hence the choice of 10 s tests. Second, the amount of tags on the board and the distance between the tags could have played a role. From experiment 4 there could be concluded that the range might be a bit larger when fewer tags would have been used. A deliberation had to be made between the resolution of the test on one hand and the effect of interference on the other hand. For positions of the tags, a target area was defined above the trough. This is likely to be quite accurate, although pigs can have one tag outside of the feeder when feeding from the side of the trough or vice-versa. Finally, the resolution of the tags inside the positive registration area and outside that area and the heights and orientations tested had an influence on the sensitivities, specificities and agreements calculated. Again a reasonable choice was made to test 7 heights, 7 orientations and with a ratio of tags in the positive area versus tags outside the positive area of 2 to 5.

The tests were sometimes impaired due to the occurring ‘RF communication errors’. This may have been due to detuning of the antenna (a drift in the resonance frequency due to eddy currents appearing in metal or other conductive materials exposed to an electromagnetic field). These eddy currents produce a magnetic field opposing the original field, causing an increase in the resonance frequency and a reduction in effectiveness of the RFID system (D’hoe et al., 2009; Ciudad et al., 2010). Both the tags and antenna contain metal, thus a large number of tags close to each other and to the antenna could cause this detuning effect. This would hinder the tags from being properly powered and would also increase the time needed for the anti-collision algorithm to be able to make a distinction between the tags in range. If the transponders’ messages cannot be decoded during the identification time assigned to that antenna by the multiplexer, the data is lost. From experiment 3 it was clear that for the boards where many transponders were in range of the antenna (boards II and III), the number of lost tests due to the read errors was much higher than for boards I and IV. This supports the hypothesis that the errors were caused by detuning.

Movement of the tags hinders the development of the opposing electromagnetic field (due to the slightly changing environmental conditions and orientation of the antenna’s electromagnetic field) and thus reduces the occurrence of detuning. Because pigs also moved their ears and bodies during feeding and because considerably fewer tags were near the antenna when pigs were feeding than during the experiments described, the occurrence of errors during experiments with pigs was considerably lower (based on unpublished results). Therefore, it is expected that these errors will not impair the performance of the system in registering feeding pigs in practical situations. Indeed, only 0.14 % of the registration cycles were hindered by ‘RF communication errors’ during five days of a fattening period with 295 tags attached to pigs in the pig house with all eight HF RFID antennas active. This low percentage did not significantly affect the registration of the feeding patterns of the pigs and should not pose a problem in commercial situations.

The reproducibility of the results between tags, tag sides, antennas and antenna quadrants was very high (minimum 96 % average agreement between tag orders, tag sides, antennas and antenna quadrants). This means that different tags and antennas had little effect on the RFID registrations, and both sides of the transponders were performing equally. Also, the range of the antennas was symmetrical, which was a prerequisite for the tests in experiment 3 where the range of only a quarter of one antenna was measured for different orientations of the tags (due to the set-up of boards II, III and IV, that had a different orientation of tags on the left and right side of the board, Figure 3). The repeatability of the tests was very high (99.1 % average agreement). It is also visually clear that the range of the antenna was spherical (the electromagnetic field generated by the antenna conforms to this spherical shape). Any lack of registrations around x-position zero in the graphs of Figure 4, Figure 5 and Figure 6 (close to the middle of the feeder) was due to a small gap between board and feeder. This caused those positions to lie a bit further from the antenna than the positions at the left or right side of the feeder (Cfr. Figure 2a for conventions of 'left' and 'right').

Orientation and position of the tags did have a noticeable effect on the detection range of the HF RFID system (Figure 6). The interrogation zone (and the coupling between RFID tags and antenna) depends on the position and orientation of the transponder coil versus the antenna coil and the magnetic field lines generated by the antenna (Finkenzeller, 2010). It is logical that the transponders placed under 90° with the horizontal plane and their central axis parallel to tangents to the antenna (see Figure 3, board II, right side) are not being registered, as the magnetic field lines do not pass through the coil of the tags. In this case the tags do not get enough power from the antenna to be activated and do not transmit their tag code to the antenna. Similarly, the other registered ranges in Figure 6 can be explained by looking at the theory behind inductive coupling (see Finkenzeller, 2010: Chapter 4 and Figure 4.24 for a more detailed description and figure about the effects of orientation of the tag on the range of the RFID system). No remarkable peculiarities or deficiencies could be observed in the measured ranges.

The sensitivity and specificity of the range of the RFID system varied greatly between heights of the board and orientation of the transponders (Table 6). No specific orientation of tags can be linked to feeding. With the design of the feeders used, feed is only dispersed when the pendulum at the bottom of the feeder is being moved (yellow part in Figure 2a) and pigs are thus encouraged to perform rooting behaviour. This can lead to large head movements and all orientations that were tested have been seen in feeding pigs (unpublished results).

The values of the specificity did not form a problem (87.1 % ± 19.4 pp (mean ± SD)); the specificity only dropped for specific orientations and for heights close to the antenna. Some tags were registered at some orientations at a maximum of 15 cm outside of the feeding trough. This means that pigs outside the feeding trough area would only be detected erroneously when standing very close to the antenna. A pig whose ears come that close to the feeder is likely to engage in feeding. In practice we can imagine this can be a pig approaching the feeder, biting the feeder or antenna or standing next to the feeder. For health monitoring, only the latter forms a problem, because this can be a pig that is trying to reach the feeder but is not able to (Maselyne et al., 2014). If this is a change in behaviour, this could result in a detectable change in the feeding pattern however. In a previous study we found that the specificity of the RFID system in discriminating feeding pigs from non-feeding pigs was always very high (Maselyne et al., 2014).

The sensitivity was very low for some heights and orientations (Table 6), which resulted in a low average sensitivity and high standard deviation (51.0 % ± 43.1 pp (mean ± SD)). Seeing these values, one could doubt the applicability of the system. However, sensitivity was very high for some orientations (Table 6), and in total the percentage of successful reads was quite high in the two-inner circles of the board (covering the feeder), for all heights higher than 20 cm (Table 4). The system could thus be applicable for pigs, but further research is needed. The lower sensitivity is most likely to form a problem when pigs are feeding constantly in a position that makes it difficult to register or when feeding visits are frequently short (Maselyne et al., 2014). Then entire feeding visits can be missed and these cannot be reconstructed by clustering registrations.

The low and varying sensitivity corresponds to the results previously obtained during the validation of the system for registering feeding pigs (Maselyne et al., 2014), where we found that gaps of varying lengths occurred between RFID registrations of feeding pigs that were larger than a normal cycle time. Pigs move their ears and their head while feeding, which causes the orientation and position of the tags to change during feeding. The tag can thus possibly move in and out of range of the antenna during feeding. The sensitivity of the HF RFID system for detecting feeding pigs could be made sufficiently high for practical use by accepting that the registrations of a pig during feeding can have time gaps of multiple seconds between them and taking this into account for the analysis of the RFID registrations. Having two tags per pig – one on each ear – with each one having a different instantaneous orientation and position also increased this sensitivity (Maselyne et al., 2014). The disadvantage of using two tags would be the higher costs (although the RFID tags can be re-used easily if the ear tags are removed from the pig) and workload for the farmer (inserting/removing the tags). The number of ear tags a pig is allowed to wear could be a limiting factor, but the HF RFID tags could be added to any type of normal ear tag, so this should not pose a problem.

We have to remark that the distance between the pigs and the antenna will influence the quality of the registrations. At the beginning of the fattening period, the pigs' ears are 15 to 30 cm from the ground. This may cause the registrations to be less frequent than for larger pigs. To solve this problem, ideally, the height of the RFID antennas should be gradually adjusted throughout the fattening period to follow the growth of the pigs. This was impossible in the current set-up due to the construction of the feeder. We suggest using two positions for the RFID antennas: a height of 46 cm for small pigs (the lowest height possible without getting too close to some metal parts of the feeder) and a height of 50 cm (the range measurements presented here were shown for this height). The 50-cm height should be used for larger pigs as they would otherwise touch the antenna with their shoulders while feeding.

Other ways to improve the sensitivity might be to increase the power input to the antennas and therefore the range. This would decrease the specificity however, but not change the fact that some orientations are hardly registered. A more directional antenna could also be an improvement, but this would require a change in technology (no inductive coupling). Ultra High Frequency (UHF) RFID might be a possibility, but the detrimental effect of metal and water in the neighbourhood of the RFID system increases with increasing frequency, as does interference, so applicability of UHF RFID might be more challenging. Read ranges are typically higher as well, which is not desired in this case (Ruiz-Garcia and Lunadei, 2011). Establishing a good read range for all orientations of tags would require multiple antennas per feeder, which would increase the cost. Changing the feeder design, such as blocking pigs that are not feeding from the area around the feeder, would simplify the measurements, but would also change the feeding behaviour and reduce ease of access to the feeder. The feeder design used here, with a round metal open trough accessible from all sides, could be one of the most challenging commercial feeders to design an RFID system for. Still the results were satisfactory, giving the conditions.

Because not all pigs have the same size, ear posture or behaviour, individual differences between registrations of pigs will remain. Differences in RFID performance throughout time (due to increasing age and size of the pigs) will also be present. Therefore, care must be taken when analysing and interpreting feeding pattern data originating from the HF RFID system presented here. Interpretation should account for a possible time trend in the data that could originate both from the effect of age on the feeding pattern as well as the RFID registrations. Therefore, further research should focus on the development of algorithms or criteria to extract the feeding pattern of individual pigs at different ages from the RFID data.

6. CONCLUSIONS

The detection range of a HF RFID system for registering feeding pigs was measured on-site. Tag, tag side, antenna and antenna quadrant were found to have negligible influence on the range of the system. Tag position and orientation did have a large influence, however. The specificity of the RFID range was generally high, but the sensitivity (how well the measured range covered the area above the feeding trough) varied according to tag orientation and the distance between tags and antenna. This result was expected, as HF RFID is based on the principle of inductive coupling between tag and antenna. It is thus recommended to adjust the height of the RFID antenna to the size of the pigs to improve the system's performance. Also, movements of the ears of the pigs can change tag orientation, creating irregular gaps between RFID registrations of a feeding pig. Further work is therefore needed to derive the feeding patterns of individual pigs from the raw RFID data, to further determine the applicability of the system.

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